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Nuclear Thermodynamics of the Heaviest Elements

by

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NUCLEAR THERMODYNAMICS OF THE HEAVIEST ELEMENTS

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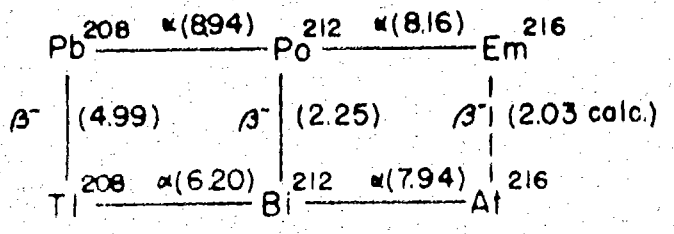
INTRODUCTION

The phenomenon of alpha particle emission, a general observable property for the nuclides above lead, makes it possible to relate these nuclides energetically. The radioactive decay energy along a radioactive series can be summed so that the total decay energy for each nuclide in the series is known with respect to its position above the bottom of the series, that is, with respect to its terminal lead (or bismuth) isotope. This can be done for each of the four mass types and, as we shall see, one can obtain this information for all the collateral members as well as the members in the main line of decay. Thus it is possible, using the relation between mass and energy and the known mass of the alpha particle, to convert this radioactive decay energy in each case to a relative mass value based on the mass of one of the four end products, Pb^{208}, Pb^{207}, Pb^{206}, or Bi^{209}. If the absolute mass of each of these is known, it is then possible to calculate the absolute mass for all the heavy nuclides above lead for which decay energy data are known or can be estimated. The absolute mass of only one of this group of four need actually be known since the neutron binding energies relating them can be measured. It is also possible to measure the absolute masses of other nuclei in each of the four series, for example, such nuclides as U^{238}, Th^{232}, U^{235}, or Np^{237} which are available in sufficient quantity for mass spectrographic measurements, and the absolute masses of the other members of each of the series may then be calculated from these through proper use of the decay data. If the absolute masses of more than one member of the same mass type is known, it is possible to have a check on the accuracy of the radioactive decay values. Once all the masses of the heavy nuclides are known accurately, it is possible to construct the energy surfaces corresponding to this region and to study the energetics of the heavy region as a whole. The present paper is concerned with the use of the radioactive, neutron-binding and mass spectrographic data for the calculation of the relative and absolute masses of the translead nuclides and the use of these in connection with the energy surface and general energetics of this region.

ACCUMULATIVE DECAY ENERGY

The calculation of accumulative decay energy can best be illustrated with an example. The following diagram illustrates the course of decay of a number of radioactive nuclides whose terminal product is Pb^{208}.



In these "closed decay cycles" the total decay energies are given in Mev and correspond to the disintegration energies. Thus the energy corresponds to the transition between the ground states of the initial and final nuclei and includes the energy of recoil which for alpha decay amounts to about 2 percent of the particle energy.

It is implicit in these thermodynamic cycles that the decay energy between any two nuclides must be a constant irrespective of the path. For example Bi^{212} (ThC) has 11.19 Mev decay energy with respect to Pb^{208} both in its decay through Po^{212} (ThC') and through Tl^{208} (ThC''). As we shall see the mass of Bi^{212} relative to Pb^{208} is determined if the mass of the alpha particle (or more properly the helium atom) is brought into the calculations. Proceeding a step further it can be seen that Em^{216} has 17.10 Mev and At^{216} 19.13 Mev decay energy with respect to Pb^{208}. Since At^{216} and Em^{216} are neighboring isobars it is obvious that At^{216} is a negative beta particle emitter unstable by 2.03 Mev although this energy has not yet been measured nor indeed has the mode of decay been observed.

This process can be continued to include all the nuclei of this mass type. There is, of course, some difficulty in choosing the disintegration energy for a number of the beta particle emitters, due to the complexity of the decay schemes, and this is sometimes also true for the alpha particle emitters. For the nuclei which decay by electron capture, such decay cycles afford the only presently feasible method for obtaining the decay energy.

This summation can be done for each of the four mass types. The results are presented diagrammatically in Figures 1-4 in a form thought to be the most useful for the present purpose. The disintegration energies in these diagrams are those which are deemed best as a result of a careful survey of the literature. The energies are the total disintegration energies in each case and are given in units of Mev. The values without superscripts are the results of measurement, whereas a superscript "c" denotes that the value comes from a calculation as in the above illustration, while the superscript "e" signifies that the energy value has been estimated. For the alpha decay process, the estimations are made by extrapolation and linear interpolation from the measured values using for each element the plot of mass numbers versus alpha energies in the systematics of alpha radioactivity. The beta disintegration energies were estimated by regular extrapolations from the measured beta disintegration energies of neighboring nuclides, taking into account the mass type and the properties of nuclides occupying analogous positions in relation to the beta stable isotopes of their respective elements. The decay energies are not presented in a summed form since it seems more useful to convert them to masses and present the information in this form for each of the nuclides and this is done in the following section. It should be emphasized that the estimation of unmeasured decay energies in the manner described is based on the assumption of a smooth energy surface in the region concerned, and if there is a region of special stability in the neighborhood of 148 neutrons, as may turn out to be the case on the basis of shell structure considerations, the resultant masses for the nuclei in the area of 148 and more neutrons will be incorrect.

TABLE OF MASSES

The four mass types are interrelated through neutron binding energies and can be tied together if three of these are known, for example, Pb^{206}-Pb^{207}, Pb^{207}-Pb^{208}, and Pb^{208}-Pb^{209} (since the disintegration energy for $Pb^{209} \xrightarrow{\beta^-} Bi^{209}$ is known). There are various ways of measuring these neutron binding energies, including the determination of the energy thresholds for reactions like $Pb^{207}(\gamma,n)Pb^{206}$, the determination of the energy of the gamma rays corresponding to the transition to the ground state in reactions like $Pb^{207}(n,\gamma)Pb^{208}$ and the measurement of the energies of the deuterons and protons in reactions like $Pb^{208}(d,p)Pb^{209}$. Such measurements lead to the following average best values for the neutron binding energies: 6.70 Mev for Pb^{206}-Pb^{207}, 7.37 Mev for Pb^{207}-Pb^{208}, and 3.88 Mev for Pb^{208}-Pb^{209}. These values, together with the above described accumulative decay energies, make it possible to calculate the

relative masses of all the heavy nuclides for which decay data are known and such relative values are suitable for many purposes. However, it is also possible to obtain all the masses on an absolute scale if at least one mass in this region is known on this scale (that is, on the scale of O^{16} = 16.000). The mass of Pb^{208} has been determined by the mass spectrographic doublet method with the value 208.04340, although this corresponds to more significant figures than are justified from the accuracy of the determination, some for the radioactive decay data are known with that accuracy and therefore the masses have been calculated to the fifth decimal place in order to reflect the relative accuracy. Using this mass together with the above mentioned neutron binding energies, and taking the mass of the neutron as 1.00897, we obtain 206.04057 as the mass for Pb^{206}, 207.04235 as the mass for Pb^{207}, and 209.04820 as the mass for Pb^{209}. With these figures as base values, together with the radioactive decay energies from Figures 1-4, and using 4.00387 for the mass of He^4, the masses of the heavy nuclides have been calculated and are given in the first column of Table 1.

A number of neutron binding energies have been determined in the region of uranium and thorium through the use of reactions such as: $U^{238}(\gamma, n)U^{237}$, $U^{238}(d, p)U^{239}$, $Th^{232}(\gamma, n)Th^{231}$, and $Th^{232}(d, p)Th^{233}$ and these should constitute a stringent test of the accuracy of the data in Table 1; the neutron binding energies calculated from the mass values in Table 1, included in a summary of neutron binding energies in that table, all agree within experimental error with the measured values. The absolute masses of some members of the decay series, such as U^{238}, U^{234}, and Th^{232}, have been obtained by the method of doublets, however these differ slightly more than their quoted limits of error from the corresponding values in Table 1.

An interesting aspect of the data in Table 1 is the possibility of calculating atomic weights on the chemical scale, which differs from the physical scale (the basis used in Table 1) in that the natural mixture of oxygen isotopes is taken to have the atomic weight exactly 16.0000 rather than using the basis O^{16}=16.0000. It is instructive to compare the values so calculated with those of the Commission on Atomic Weights of the International Union of Chemistry as follows, in which the value calculated from the data in Table 1 is given first followed by the presently accepted chemical atomic weight: Pb 207.19 (207.21), Bi 208.99 (209.00), Ra 226.04 (226.05), Th 232.05 (232.12) and U 238.03 (238.07). (In order to calculate a mass for Pb^{204}, not given in Table 1, a two neutron binding energy of 14 Mev was used for Pb^{206}-Pb^{204}.) Since the values in Table 1 should not be in error by more than 0.01 atomic weight unit, and probably are in error by less than this much, it is apparent that it will be necessary to change some of the officially accepted values.

NEUTRON BINDING ENERGIES

There are a number of interesting regularities to be considered as the result of further treatment of the mass data. One of these is the variation of neutron binding energy with mass number for each of the elements. Also of interest are the various trends in proton binding energies. For both neutrons and protons the combined binding energy of two particles is of special interest because of the pairing effect. The neutron and proton binding energies can readily be calculated from the masses given in Table 1 and this has been done, again using the value 1.00897 for the mass of the neutron and using 1.00814 for the mass of hydrogen. The binding energies for one and two neutrons and for one and two protons have been calculated for the translead nuclides (acutally including lead and thallium) and are also included in Table 1.

These binding energies do not exhibit smooth trends in all instances and perhaps the mass values should be adjusted so that for example, a smooth variation for each mass type of the neutron or two neutron binding energy

with mass number is exhibited for each element; such smooth trends might reasonably be expected and therefore such adjustments might lead to better mass values on the whole. However it was decided to present in this report the mass data as calculated from the experimental radioactive decay and neutron binding data without this adjustment, with the thought that further study of this and other factors might point the way to a better method of treatment which takes into account such trends of regularity. The irregularities are most pronounced in the region of the heavier transuranium elements where the extrapolations are most severe and surely subject to appreciable errors.

The break in neutron binding energy at the closed shell of 126 neutrons is very apparent from the data in Table 1, with the binding energies for the neutrons beyond 126 some 2 to 3 Mev less than those for nuclei of the same mass type with 126 neutrons or less.

ENERGY SURFACE

A very interesting use of the mass data is for the purpose of construction of an energy surface for the entire heavy nuclide region. There are actually three energy surfaces to be considered, one corresponding to all the nuclides with odd masses and the other two corresponding to the even-even and odd-odd types with even masses, possibly the odd mass types are also to be separated into two surfaces corresponding to the even-odd and odd-even types but these differ only a little. The data are not sufficiently extensive to consider all types, but there does seem to be sufficient information to construct a surface corresponding to the odd masses. There are several choices as to what function of the mass and what relationships between the neutrons and protons should be plotted as coordinates. Figure 5 shows a photograph of an actual model of the energy surface representing the plot of the mass defect data on the z axis plotted versus Z (the atomic number) and A - Z (the neutron number) on the x and y axes for odd A nuclei.

DISCUSSION

The energy surface constructed through the use of the mass data and shown in Figure 5 shows clearly the Heisenberg valley character to be expected. The strong effect of the region of the closed shells, that is 126 neutrons and 82 protons is also apparent. Other interesting questions, such as the determination of the best fit to an equation for the calculation of the mass of a nuclide in terms of Z and A and certain parameters governing its beta instability, a possible difference between the energy of proton pairing and neutron pairing corresponding to two energy surfaces for the odd mass nuclides, trends in neutron and proton binding energies, possible additional regions of special stability, etc., require additional study of the data before they may be answered.

The data indicate which of the nuclides are beta stable (that is, stable toward the emission of negative beta particles or the capture of orbital electrons), these are analogous to the "stable" nuclides of the region below lead. These are summarized for convenience in Table 2, in some instances where the information is not available from the mass data, predictions have been made on the basis of anticipated regularities. (As mentioned above, these considerations assume a negligible contribution to stability from the 148 neutron configuration, an assumption which might very well turn out to be erroneous.)

A number of interesting observations can be made concerning the beta stable nuclides listed in Table 2. It is quite possible that the element astatine (number 85) has no beta stable isotopes, which may be a consequence of its position just beyond the 126 neutron shell. The data seem to indicate that actinon (that is, Em^{219}) is unstable toward the emission of negatrons, a fascinating possibility in view of the interesting historical position of this natural radioactivity which has always been considered to

be stable toward beta emission. The element americium (number 95) may possibly have two beta stable nuclides, with mass numbers 241 and 243, although the question of the beta stability of mass 243 is borderline; this would be analogous to those odd-Z elements with two beta stable isotopes in the region below lead. The question as to which isotope of berkelium (number 97) is beta stable is a close one, with the possibility of either mass number 247 or 249 or possibly both. The transcurium region is of course subject to the greatest doubt because this is the region where the greatest extrapolations are made.

The author wishes to express his appreciation to Richard A. Glass for help on many aspects of this subject, especially with the many calculations, and to Margie S. Hollander for help in abstracting much of the literature in connection with the large number of data on radioactive properties which had to be evaluated.

February 27, 1952

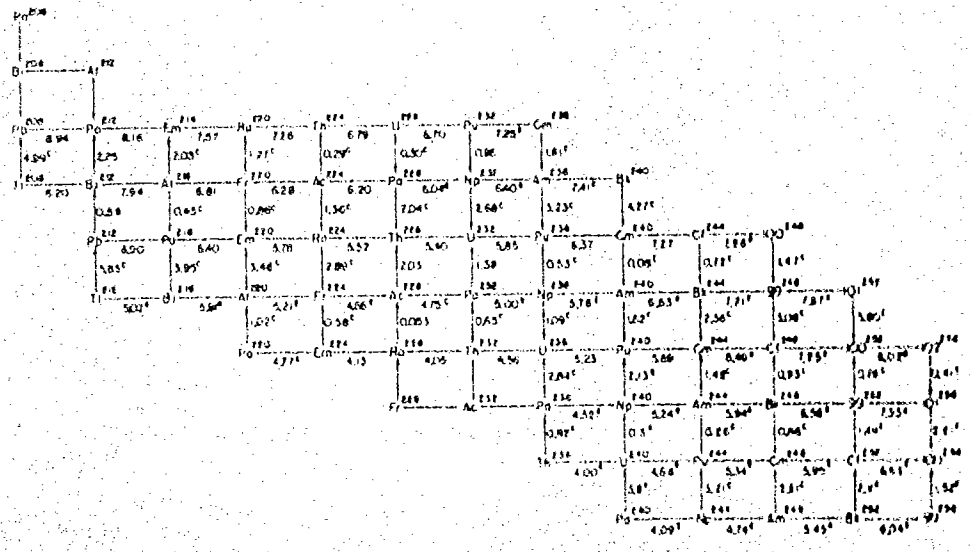


FIGURE 1. Closed radioactive decay cycles for 4n mass type. (No superscript signifies experimental disintegration energy; superscript "e" denotes estimated and "c" calculated values.)

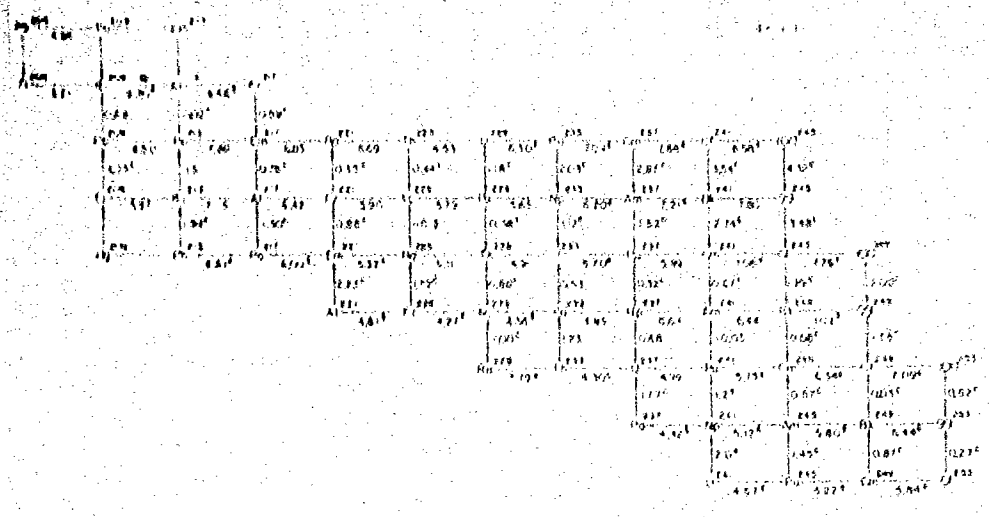


FIGURE 2. Closed radioactive decay cycles for 4n + 1 mass type. (No superscript signifies experimental disintegration energy, superscript "e" denotes estimated and "c" calculated values.)

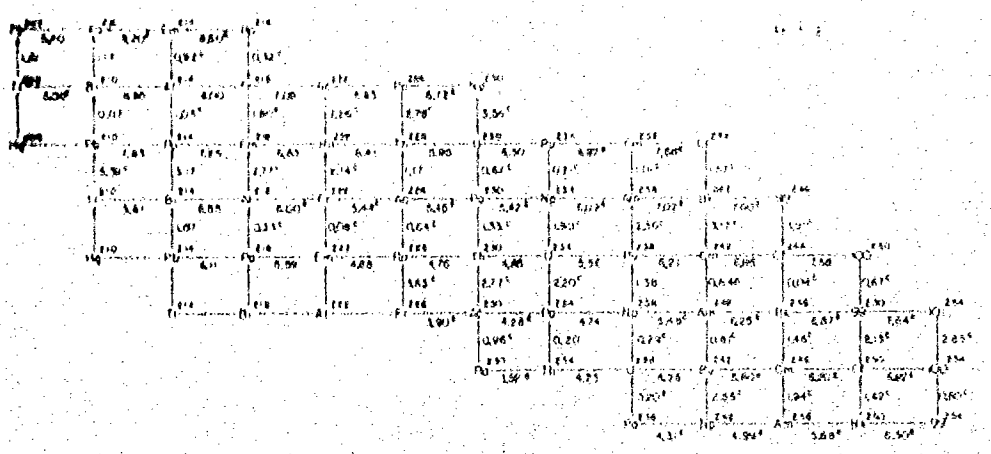


FIGURE 3. Closed radioactive decay cycles for 4n + 2 mass type. (No superscript signifies experimental disintegration energy, superscript "e" denotes estimated and "c" calculated values.)

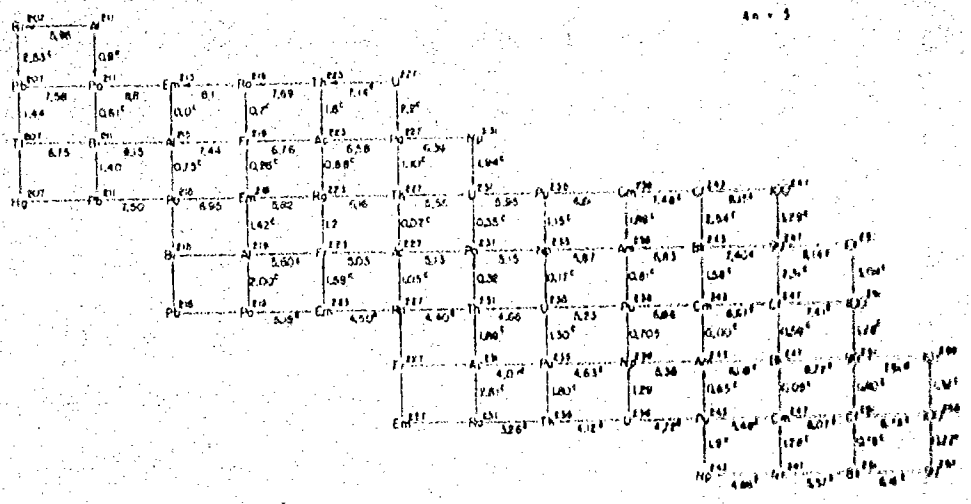


FIGURE 4. Closed radioactive decay cycles for 4n + 3 mass type. (No superscript signifies experimental disintegration energy. superscript "e" denotes estimated and "c" calculated values.)

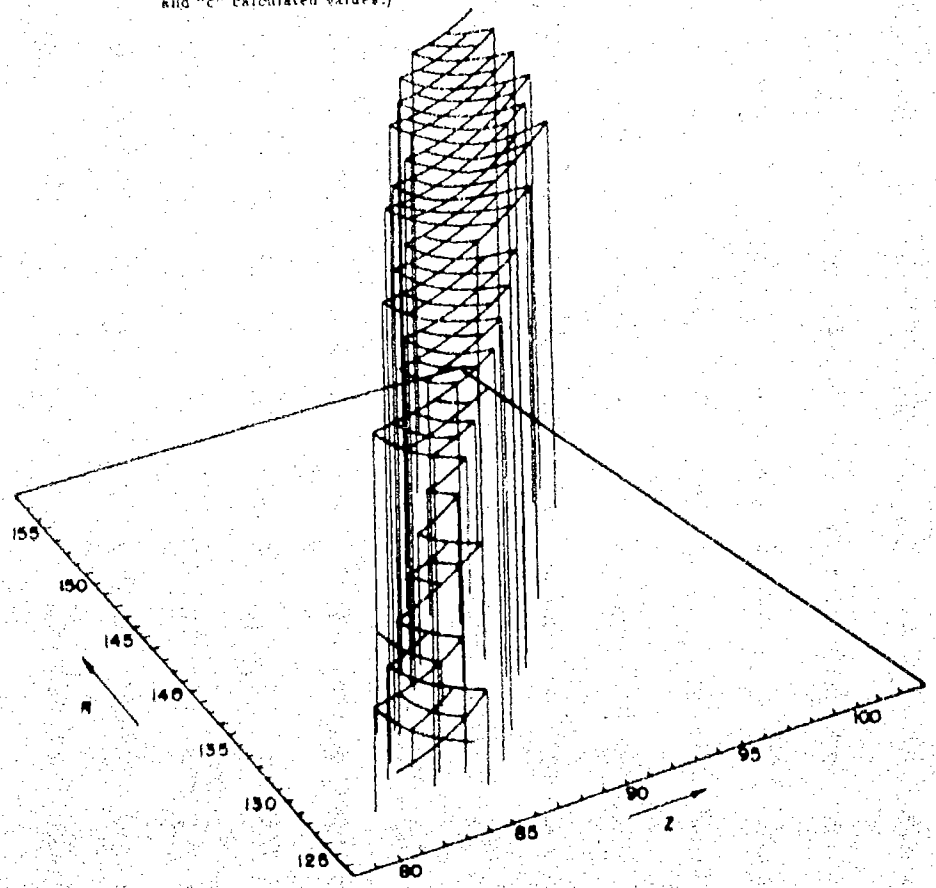


FIGURE 5. Model of Energy Surface for Odd Mass Numbers in Translead Region.

Table I

MASS AND NUETRON AND PROTON BINDING ENERGIES OF THE TRANSLEAD NUCLIDES

The bases for the following calculation are

1. Mass of Pb^{208} = 208.04340

He^4 = 4.00387
$0n^1$ = 1.00897
H^1 = 1.00814

2. Neutron binding energies:

$Pb^{206-207}$ = 6.70 Mev
$Pb^{207-208}$ = 7.37 Mev
$Pb^{208-209}$ = 3.88 Mev

3. 1 atomic mass unit = 931 Mev

Element and Mass	Binding Energy (Mev) E_0 (1 neutron)	E_{2n} (2 neutrons)	E_p (1 proton)	E_{2p} (2 protons)
81-Thallium				
205.04015				
206.04219	6.45			
207.04389	6.77	13.22		
208.04876	3.82	10.59		
209.05253	4.84	8.66		
210.05736	3.85	8.69		
211.				
212.06619		8.49		
82-Lead				
206.04057			7.19	
207.04235	6.79		7.44	
208.04340	7.37	14.07	8.04	
209.04820	3.88	11.25	8.10	
210.05157	5.21	9.09	8.47	
211.05652	3.75	8.96	8.37	
212.05992	5.18	8.93		
213.06490	3.72	8.90	8.78	
214.06841	5.08	8.80		
83-Bismuth				
207.04506			3.40	10.59
208.				
209.04747		14.46	3.79	11.82
210.05150	4.60		4.51	12.61
211.05501	5.08	9.68	4.38	12.85
212.05929	4.37	9.45	5.88	13.37
213.06281	5.07	9.44	4.89	
214.06726	4.21	9.28	5.38	14.16
215.				
216.07545		9.08		

Element and Mass	Binding Energy (Mev) E_n (1 neutron)	E_{2n} (2 neutrons)	E_p (1 Proton)	E_{2p} (2 protons)
84-Polonium				
210.05024			5.00	8.79
211.0544	4.5		4.9	9.4
212.05687	6.0	10.53	5.85	10.23
213.06120	4.32	10.3	5.80	10.80
214.06386	5.88	10.20	6.61	11.50
215.06844	4.08	9.96	6.48	11.86
216.07120	5.78	9.86		12.56
217.07576	4.11	9.89	7.29	
218.07884	5.48	9.59		
219.08345	4.06	9.54		
220.08676	5.27	9.33		
85-Astatine				
211.05532			2.85	7.85
212.				
213.06122		11.21	3.53	9.38
214.06498	4.85		4.06	9.86
215.0676	5.88	10.73	4.06	10.67
216.07169	4.58	10.46	4.56	11.03
217.07436	5.86	10.44	4.64	
218.07849	4.51	10.37	5.04	12.33
219.08130	5.73	10.24	5.29	
220.08567	4.29	10.02	5.52	
221.08847	5.74	10.03	5.99	
86-Emanation				
214.06399			5.00	8.53
215.0676	4.9		5.1	9.1
216.06951	6.7	11.57	5.84	9.89
217.07355	4.59	11.2	5.85	10.41
218.07551	6.52	11.11	6.51	11.15
219.07978	4.38	10.90	6.38	11.42
220.08195	6.33	10.71	6.98	12.26
221.08607	4.51	10.84	7.20	12.71
222.08872	5.89	10.40	7.35	13.34
223.09289	4.47	10.36		
224.09575	5.68	10.15		
87-Francium				
217.07418			3.23	9.06
218.07745	5.31		3.95	9.80
219.07950	6.44	11.75	3.87	10.38
220.08287	5.21	11.65	4.70	11.07
221.08513	6.25	11.46	4.62	11.60
222.08880	4.93	11.18	5.04	12.24
223.09119	6.13	11.06	5.28	12.63
224.09513	4.68	10.81	5.49	
225.09751	6.14	10.82	5.95	
226.10173	4.42	10.56		

Element and Mass	Binding Energy (Mev) E_n (1 neutron)	E_{2n} (2 neutrons)	E_p (1 proton)	E_{2p} (2 protons)
88-Radium				
218.07710			4.86	8.09
219.0803	5.4		5.0	8.9
220.08151	7.2	12.60	5.71	9.58
221.08475	5.33	12.5	5.83	10.53
222.08650	6.72	12.05	6.30	10.92
223.08999	5.19	11.91	6.56	11.60
224.09203	6.37	11.56	6.80	12.08
225.09566	4.97	11.34	7.09	12.57
226.09783	6.33	11.30	7.28	13.23
227.10159	4.86	11.18	7.71	
228.10406	6.05	10.90		
229.10811	4.58	10.63		
230.11082	5.83	10.41		
231.11502	4.44	10.27		
89-Actinium				
222.08893			3.69	9.52
223.09063	6.77		3.74	10.04
224.09349	5.69	12.46	4.24	10.80
225.09534	6.63	12.32	4.50	11.29
226.09852	5.39	12.02	4.92	12.01
227.10046	6.54	11.93	5.13	12.41
228.10401	5.05	11.59	5.33	13.03
229.10596	6.53	11.58	5.81	
230.10979	4.79	11.32	6.02	
231.11221	6.09	10.88	6.28	
90 - Thorium				
223.0924			4.4	8.1
224.09318	7.6		5.21	8.94
225.09581	5.90	13.5	5.48	9.71
226.09726	7.00	12.90	5.79	10.29
227.10039	5.44	12.44	5.84	10.76
228.10183	7.01	12.45	6.31	11.44
229.10502	5.38	12.39	6.64	11.96
230.10681	6.68	12.06	6.79	12.60
231.11018	4.62	11.31	7.21	13.23
232.11228	6.40	11.02	7.52	13.79
233.11605	4.84	11.24		14.19
234.11847	6.10	10.94		
235.12239	4.70	10.80		
236.12498	5.94	10.64		
91-Protactinium				
226.10025			3.45	8.92
227.10157	7.12		3.57	9.36
228.10402	6.07	13.19	4.20	10.04
229.10543	7.04	13.11	4.23	10.54
230.10824	5.73	12.77	4.58	11.22
231.10984	6.86	12.59	4.76	11.55
232.11298	5.43	12.29	4.98	12.18
233.11473	6.72	12.15	5.30	12.81
234.11825	5.07	11.79	5.53	
235.12046	6.30	11.37	5.73	

Element and Mass	Binding Energy (Mev) E_n (1 neutron)	E_{2n} (2 neutrons)	E_p (1 proton)	E_{2p} (2 protons)
91-Protactinium (continued)				
236.12410	4.96	11.26	5.99	
237.12644	6.17	11.13	6.22	
238.13034	4.72	10.89		
239.				
240.13723		10.29		
92-Uranium				
227.1039			4.2	7.6
228.10434	8.0		5.00	8.57
229.10669	6.16	14.1	5.09	9.29
230.10752	7.58	13.74	5.63	9.86
231.11022	5.84	13.42	5.74	10.32
232.11150	7.16	13.00	6.04	10.80
233.11416	5.87	13.03	6.48	11.46
234.11589	6.74	12.61	6.50	11.80
235.11906	5.40	12.14	6.83	12.36
236.12105	6.50	11.90	7.03	12.75
237.12454	5.10	11.60	7.17	13.15
238.12690	6.15	11.25	7.15	13.37
239.13069	4.83	10.98	7.26	
240.13315	6.06	10.89		
241.13721	4.57	10.63	7.60	
93-Neptunium				
230.11133			3.26	8.35
231.11230	7.45		3.13	8.76
232.11438	6.42	13.87	3.71	9.45
233.11536	7.43	13.85	3.98	10.02
234.11793	5.96	13.39	4.07	10.55
235.11924	7.13	13.09	4.46	10.96
236.12222	5.58	12.71	4.64	11.47
237.12381	6.87	12.45	5.01	12.04
238.12722	5.18	12.05	5.17	12.34
239.12930	6.41	11.59	5.35	12.50
240.13282	5.07	11.48	5.59	12.85
241.13506	6.27	11.34	5.80	
242.13884	4.83	11.10	6.09	13.69
243.14167	5.72	10.55		
244.14549	4.79	10.51		
94-Plutonium				
232.11541			4.69	7.82
233.11755	6.36		4.63	8.33
234.11816	7.78	14.14	4.98	8.96
235.12048	6.19	13.97	5.21	9.28
236.12165	7.26	13.45	5.34	9.80
237.12415	6.02	13.28	5.78	10.41
238.12573	6.88	12.90	5.79	10.80
239.12855	5.73	12.61	6.34	11.51
240.13054	6.50	12.23	6.43	11.78
241.13377	5.34	11.84	6.70	12.29
242.13610	6.18	11.52	6.61	12.41
243.13963	5.07	11.25	6.85	12.94

Element and Mass	Binding Energy (Mev) En (1 neutron)	E2n (2 neutrons)	Ep (1 proton)	E2p (2 protons)
95-Americium (continued)				
244.14294	6.10	11.17	7.23	
245.14599	4.68	10.78	7.12	
96-Curium				
236.12517			3.26	8.47
237.12589	7.63		4.63	8.96
238.12827	6.14	13.77	3.75	9.53
239.12942	7.28	13.42	4.15	9.94
240.13228	5.69	12.97	4.11	10.45
241.13374	6.99	12.68	4.60	11.03
242.13697	5.34	12.33	4.60	11.30
243.13893	6.53	11.87	4.95	11.56
244.14232	5.19	11.72	5.07	11.92
245.14443	6.46	11.65	5.36	12.58
246.14807	4.96	11.42	5.64	12.76
247.15076	5.05	10.81		
248.15445	4.91	10.76		
96-Curium				
236.12706				6.86
237.12898	6.57		3.99	7.25
238.12935	8.00	14.57	4.36	7.99
239.13145	6.40	14.40	4.62	8.37
240.13236	7.50	13.90	4.84	8.99
241.13446	6.40	13.90	5.55	9.66
242.13627	6.66	13.06	5.22	9.82
243.13893	5.88	12.54	5.76	10.36
244.14073	6.67	12.55	5.90	10.84
245.14382	5.48	12.15	6.19	11.25
246.14599	6.33	11.81	6.13	11.49
247.14938	5.19	11.52	6.36	12.00
248.15165	6.24	11.43	6.75	
249.15546	4.80	11.04	6.64	
97-Berkelium				
240.13695			2.46	7.08
241.13751	7.83		2.79	7.62
242.13968	6.33	14.16	2.72	8.27
243.14062	7.47	13.80	3.53	8.75
244.14327	5.89	13.36	3.54	9.29
245.14453	7.18	13.07	4.05	9.94
246.14755	5.53	12.71	4.10	10.29
247.14933	6.70	12.23	4.47	10.60
248.15257	5.33	12.03	4.61	10.97
249.15453	6.53	11.86	4.90	11.64
250.15804	5.08	11.61	5.18	11.82
251.16061	5.96	11.04		
252.16418	5.03	10.99		
98-Californium				
241.14131			3.52	5.97
242.14147	8.29		3.89	6.68
243.14335	6.60	14.80	4.16	6.88

Element and Mass	Binding Energy (Mev) E_n (1 neutron)	E_{2n} (2 neutrons)	E_p (1 proton)	E_{2p} (2 protons)
98-Californium (continued)				
244.14404	7.71	14.31	4.40	7.93
245.14591	6.61	14.32	5.12	8.66
246.14751	6.86	13.47	4.80	8.85
247.14996	6.07	12.93	5.34	9.44
248.15157	6.85	12.92	5.49	9.95
249.15450	5.63	12.48	5.79	10.40
250.15652	6.47	12.10	5.73	10.63
251.15977	5.32	11.79	5.97	11.15
252.16191	6.36	11.68	6.37	
253.16561	4.91	11.27	6.25	
99-				
245.14976			2.26	6.66
246.15171	6.53		2.18	7.30
247.15244	7.67	14.20	2.99	7.79
248.15488	6.08	13.75	3.00	8.33
249.15595	7.36	13.44	3.51	8.99
250.15880	5.69	13.05	3.57	9.36
251.16042	6.85	12.54	3.95	9.68
252.16351	5.47	12.32	4.10	10.07
253.16532	6.67	12.14	4.41	10.77
254.16868	5.22	11.89	4.72	10.97
255.17110	6.10	11.32		
256.17453	5.15	11.25		
100-				
245.15440				4.87
246.				
247.15598		15.23	3.61	5.79
248.15646	7.90		3.84	6.83
249.15812	6.81	14.71	4.57	7.56
250.15952	7.04	13.85	4.25	7.76
251.16179	6.24	13.28	4.80	8.37
252.16323	7.01	13.25	4.96	8.91
253.16598	5.79	12.80	5.28	9.37
254.16782	6.64	12.43	5.25	9.66
255.17092	5.46	12.10	5.49	10.21
256.17290	6.51	11.97	5.90	
101-				
251.16506			2.43	6.68
252.16731	6.25		2.44	7.23
253.				
254.17088		13.38	3.02	8.30
255.17234	6.99		3.37	8.62
256.17528	5.62	12.61	3.53	9.02
102-				
255.				
256.17572			4.44	7.80

Table 2

BETA STABLE NUCLIDES IN TRANSLEAD REGION

83	Bismuth	209
84	Polonium	210, 211, 212,213, 214, 216
85	Astatine	?
86	Emanation	214, 216, 217, 218, 220, 222
87	Francium	219
88	Radium	218, 220, 221, 222, 223, 224, 226
89	Actinium	225
90	Thorium	224, 226, 227, 228, 229, 230, 232
91	Protactinium	231
92	Uranium	230, 232, 233, 234, 235, 236, 238
93	Neptunium	237
94	Plutonium	236, 238, 239, 240, 242, 244 (?)
95	Americium	241, 243 (?)
96	Curium	242, 243(?), 244, 245, 246, 248, 250
97	Berkelium	247(?), 249(?)
98	Californium	246(?), 248, 249, 250, 251, 252, 254
99	-	253
100	-	252, 254, 255, 256

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